

**Intellectual Mobility:
Native Responses to Supply Shocks in the Space of Ideas**

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We argue that in response to supply shocks workers not only move from one job to another or from one geographic location to another, but also move in the more intangible space of ideas. Knowledge producers who are conducting research on a particular set of questions may respond to supply and demand shocks by shifting their resources to a different set of questions. Intellectual mobility thus measures the transition from one location in idea space to another location in that space. This paper examines the intellectual mobility flows unleashed by the influx of a large number of Soviet mathematicians into the United States after the collapse of the Soviet Union. Our analysis exploits the fact that the influx of Soviet mathematicians into the American mathematics community was larger in some fields than in others. Constructing several new empirical measures of intellectual mobility, we find substantial intellectual mobility in response to the influx, with American mathematicians moving away from, rather than moving to, fields that likely received large numbers of Soviet émigrés. It appears that diminishing returns in specific research areas, rather than beneficial human capital spillovers, dominated the intellectual mobility decisions of pre-existing knowledge producers. Our analysis also begins to shed light into the black box of the intellectual mobility decision by delineating some of its determinants. We consistently observe that high-quality mathematicians were less likely to move to a different location in the space of ideas in response to the Soviet supply shock. Interpreting this finding through the lens of a Roy-type framework of intellectual mobility, the evidence suggests that high quality mathematicians either have higher mobility costs or gain larger positive spillovers from interacting with other knowledge producers.

Intellectual Mobility: Native Responses to Supply Shocks in the Space of Ideas

George J. Borjas and Kirk B. Doran*

I. Introduction

Beginning with Sjaastad (1962), the study of mobility has been a central area of concern in labor economics. There have been countless studies of the determinants and consequences of, for example, job mobility, geographic mobility, and occupational mobility. These studies have typically been motivated by the insight that mobility plays a central role in allowing labor markets to re-equilibrate in response to supply and demand shocks, and that these flows improve labor market efficiency.

This paper introduces and examines the economics of a new type of mobility: intellectual mobility. We argue that in response to shocks workers not only move from one job to another, or from one geographic location to another, but also move in the more abstract space of ideas.¹ Knowledge producers who are conducting research on a particular set of questions may respond to supply and demand shocks by shifting their resources to analyze a different set of questions. Intellectual mobility thus measures the transition from one location in idea space to another location in that space.

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¹ The social sciences literature on the behavior of scientists and mathematicians has examined intellectual mobility (or "cognitive mobility") from a descriptive perspective in Wagner Dobler (1999), Basu (2011), and Basu and Wagner Dobler (2012). The authors use intellectual migration between the fields of mathematics to determine which fields are "closer" to each other.

A number of recent studies (Azoulay, Zivin and Wang, 2010; and Waldinger, 2009, 2012) suggest that the entry of high-skill researchers influence the productivity of those workers who are *intellectually* close to them at least as much as they influence the productivity of natives who are geographically close.² This finding suggests that the costs and benefits of high-skill immigration of scientists and knowledge producers cannot be evaluated without documenting whether natives change the type of intellectual work that they engage in as a response. This is a difficult question that has not yet been addressed by the literature, mainly because answering it depends on determining the intellectual content of individual researchers' contributions over time.

In this paper, we examine how natives reallocate themselves in idea space as a result of a supply shock that greatly increased the number of knowledge producers working on specific topics.³ In particular, we examine the intellectual mobility of American mathematicians triggered by the influx of Soviet mathematicians after the collapse of the Soviet Union in the early 1990s. The supply response can be either positive or negative, depending on whether spillover effects resulting from the increase in the size of the stock of ideas or the scarcity constraints implied by the law of diminishing returns dominate. As a result, the evidence of intellectual mobility provides independent confirmation about the relative importance of human capital spillovers in the knowledge production sector.

² See also: Furman, Kyle, Cockburn, and Henderson (2011); Hunt and Gauthier-Loiselle (2010); Kerr and Lincoln (2010); and Moser, Voena, and Waldinger (2012).

³ Intellectual mobility, of course, can also result from demand shocks. A simple anecdotal example will suffice: The study of the “Great Moderation” seems to have been an important topic in macroeconomics between 2000 and 2008. However, the financial crisis of 2009 and the severe subsequent recession likely motivated many of the macroeconomists studying the presumed taming of the business cycle to find more fertile (and publishable) areas of research.

We make use of the fact that this supply shock varied significantly in magnitude across locations in the space of ideas, as shown in Borjas and Doran (2012). That paper examined the impact of the collapse of the Soviet Union on the rate of output of American mathematicians. Nearly 10 percent of the Soviet mathematical workforce left the country after its political (and economic) unraveling, with a disproportionate number settling in the United States. Borjas and Doran (2012) showed that the increased number of mathematicians in the United States led to a significant decrease in the volume of scientific output of competing American mathematicians.⁴

Our data consist of a complete tabulation of publications of all American mathematicians between 1940 and 2009, including detailed information on the “field” of each publication.⁵ Hence we can examine the evolution of research topics and interests over a particular mathematician’s working life. We find striking evidence that the supply shock generated a strong response in terms of intellectual mobility: pre-existing American mathematicians relocated within idea space to research topics and questions that did not receive a large number of Soviet émigrés. We also document that new entrants to the American mathematics community began to systematically avoid Soviet-style topics over the two-decade period after the Soviet influx.

The analysis identifies costs that are correlated with intellectual mobility, and shows that the Soviet influx increased those costs for a significant number of American mathematicians. In particular, our data reveal that mathematicians who move intellectually

⁴ An important analysis of the codified knowledge flows related to this shock, as measured by book translations, is in Abramitzky and Sin (2012).

⁵ Dubois, Rochet, and Schlenker (2012) carefully use a subset of this data to analyze the correlates of the geographic mobility of mathematicians.

take longer to produce their next paper than mathematicians who stay within their comfort zone and continue working in fields where they have previous experience. In addition to the fact that the Soviet influx increased the number of intellectual movers (and hence increased the length of the average “preparation spell” for the next paper), we also find that the length of the preparation spell itself increased significantly for those American mathematicians who experienced the stiffest intellectual competition from the Soviet émigrés. This evidence is consistent with the notion of congestion costs, as many mathematicians who work in one narrow area try to intellectually move at once to another area.

Finally, our data allows us to examine some of the determinants of intellectual mobility. In particular, we find that tenured mathematicians and mathematicians with a high rate of output prior to the Soviet supply shock were relatively less likely to intellectually move than were the younger or less productive mathematicians. This implies that either the costs of intellectual mobility were higher for skilled mathematicians, or the net benefits from human capital spillovers were higher. Given that the “excess” publication lag associated with post-Soviet intellectual mobility is lower for highly skilled mathematicians, the evidence is most consistent with the conjecture that the beneficial spillover effects resulting from the influx of highly skilled mathematicians tended to accrue most to the most productive mathematicians and/or to those with job security.

II. Conceptual Framework

Our basic model of knowledge production is inspired by modern theories of economic growth that emphasize how human capital externalities affect the productivity of

specific workers (Jones and Romer, 2012). A worker surrounded by a high skill workforce may himself become more productive through exposure to new ideas and concepts. It is well known, however, that these spillover effects must coexist with the traditional laws of scarcity and diminishing returns that form the core of economic analysis.

Consider the simplest model where the production function for “mathematical knowledge” in the United States, Y , depends on the stock of ideas A , the stock of resources K used as inputs (e.g., faculty slots and computing resources), and the stock of mathematicians L . Suppose there are constant returns to K and L and that the production function is given by:

$$(1) \quad Y = A^{\phi} (K^{\alpha} L^{1-\alpha}),$$

where ϕ gives the “externalities elasticity.” As long as the stock of ideas is proportional to the size of the workforce, it is easy to show that the short- and long-run effects of a supply shock ($m = d \log L$) on the marginal product of mathematicians is:

$$(2) \quad d \log MP_L = \begin{cases} (\phi - s_k) m, & \text{if } d \log K = 0 \\ \phi m, & \text{if } d \log K = m. \end{cases}$$

The sign of the short-run effect depends on the relative strength of the spillovers elasticity and the traditional competitive effect. Over time, however, the capital stock adjusts to the supply shock. If spillover effects exist, the long-run impact will be positive because the stock of ideas expanded, leading to an increase in worker productivity.

To introduce the notion of intellectual mobility, we allow for the possibility that the mathematics workforce is not homogenous. Mathematics, like all other disciplines, is

composed of distinct “fields.” The externality captured by ϕ is a global human capital externality: the change in the total stock of mathematical ideas shifts the productivity of *all* mathematicians by the same proportion. However, a supply shock that differentially affects the size of the workforce in, say, Geometric Topology and Quantum Theory might have different impacts on the stock of ideas useful to researchers in those two areas. It is likely, therefore, that a mathematician’s productivity depends both on global and *local* externalities.

The simplest way to incorporate the existence of different mathematical fields is to interpret the variable L as the number of efficiency units supplied by the mathematics workforce.⁶ Suppose there are F distinct mathematical fields and define the total number of efficiency units as:

$$(3) \quad L = \left(A_1^\theta L_1^\beta + \dots + A_F^\theta L_F^\beta \right)^{1/\beta},$$

where A_f gives the stock of ideas in field f ; L_f gives the size of the mathematics workforce in that field; θ is the local externality elasticity measuring the size of field-specific spillovers; and the elasticity of substitution between mathematicians working in different fields is $\sigma_F = 1/(1 - \beta)$.

For simplicity, suppose we can categorize all research in mathematics as Soviet-style research (S) or American-style research (A). Let m_S and m_A give the percent change in the number of Soviet-style and American-style mathematicians resulting from the supply shock following the collapse of the Soviet Union, with $m_S > m_A$. The impact of the supply

⁶ See Borjas and Doran (2012b) for an extended discussion of the multi-level CES framework in the human capital externalities context.

shock on the relative productivity of mathematicians working in these two general areas is then given by:⁷

$$(4) \quad d \log MP_S - d \log MP_A = \left(\theta - \frac{1}{\sigma_N} \right) (m_S - m_A),$$

in *both* the short and long runs. Note that the global externality ϕ does not affect the change in the relative marginal product since it expands the productivity of all mathematicians equally, regardless of field. Further, the distributional impact summarized by (4) persists in the long run, even after the capital stock has adjusted. Finally, the net impact of the supply shock can again be positive or negative, depending on whether the local externality elasticity θ is larger than the competitive effect measured by the inverse of the elasticity of substitution across fields.

Regardless of the direction of the net effect in equation (4), the supply shock may trigger a supply response.⁸ The sign of the net productivity impact will either induce an inflow of mathematicians from other fields into the Soviet-dominated fields (if the net effect is positive), or an outflow of mathematicians currently conducting research in the Soviet-dominated fields into those fields less affected by the supply shock (if the net effect is negative).

It is easy to describe the mechanism generating these intellectual mobility flows. Let MP_{iS} and MP_{iA} denote the marginal product of mathematician i in the Soviet- and American-style fields, respectively. An income-maximizing mathematician who decided to conduct

⁷ The derivation of equation (4) assumes that the stock of ideas in a particular field is proportional to the number of workers in that field.

⁸ See Hunt (2012) for an empirical analysis of how an immigration-induced supply shock may affect the decisions of native workers to invest in education.

research in Soviet-dominated fields *prior to the collapse of the Soviet Union* must have satisfied the inequality $MP_{iS} > MP_{iA}$. Let γ_i measure the net effect of the supply shock on the productivity of mathematician i . After the supply shock, a Soviet-style mathematician will engage in intellectual mobility and begin to conduct American-style research only if:

$$(5) \quad MP_{iS} + \gamma_i < MP_{iA} - C_i,$$

where C_i gives the costs of intellectual mobility (e.g., retooling skills, investing in establishing a new network of collaborators, perhaps moving to a new institution, etc.). We assume that these mobility costs are strictly positive. The pre-shock revealed preference of mathematician i implies that a Soviet-style mathematician will intellectually move to American-style research if and only if:

$$(6) \quad -\gamma_i - C_i > 0.$$

Since mobility costs are positive, a Soviet-style mathematician responds to the supply shock by intellectually moving to American-style research only if the net effect γ_i is strongly negative (i.e., $\gamma_i < -C_i$). Put differently, if we were to observe many Soviet-style mathematicians switching to American-style topics in the aftermath of the supply shock, this observation necessarily implies that the competitive affects arising from the supply shock must be far stronger than the positive spillovers generated by the expansion in the stock of ideas.

Similarly, consider the intellectual migration decision of mathematicians who are conducting American-style research prior to the supply shock. This subsample of

mathematicians must satisfy the inequality $MP_{iA} > MP_{iS}$. Mathematicians in this group will intellectually move to Soviet-style research after the supply shock if:

$$(7) \quad MP_{iS} + \gamma_i - C_i > MP_{iA}.$$

Because these mathematicians had an initial advantage in conducting American-style research, the observation of intellectual mobility to Soviet-style fields implies that:

$$(8) \quad \gamma_i - C_i > 0.$$

In other words, intellectual mobility from American-style to Soviet-style research implies the presence of strong positive externalities (i.e., $\gamma_i > C_i$).

It is important to emphasize that intellectual mobility will be observed only if the net spillover is numerically large *regardless of sign*. The net spillover will be strongly positive if the intellectual movers are mainly composed of mathematicians moving from American- to Soviet-style research; or they will be strongly negative if the movers flow in the opposite direction. Regardless of the sign of γ_i , the net spillover must outweigh the costs of intellectual migration. We show below that these costs are sizable and likely increased after the supply shock.⁹

⁹ It is easy to expand the model to learn more about the selection that characterizes the sample of intellectual movers. It is likely, after all, that there is a great deal of heterogeneity in the magnitude of the net externality (γ_i) and migration costs (C_i) across mathematicians. Perhaps most important, the type of selection will depend on the correlation between these two variables and a mathematician's innate ability. We provide evidence below suggesting that high-ability mathematicians either benefited the most from the human capital spillovers or had the lowest costs of intellectual mobility.

III. Historical Context and Data

Our empirical exploration of the concept and empirical relevance of intellectual mobility examines the research decisions made by mathematicians in the United States prior to and after the collapse of the Soviet Union. As documented by Borjas and Doran (2012), after a long period of infrequent contacts between Soviet and Western mathematicians, over 1,000 Soviet mathematicians (or roughly 10 percent of the stock) left the Soviet Union after 1992, with around a third settling in the United States. This particular historical event has a number of key features that play a crucial role in our identification strategy:

(1) The opportunity for large numbers of Soviet mathematicians to migrate to the United States arose unexpectedly and suddenly, beginning around the two-year period surrounding the collapse of Soviet communism in 1990-1991.

(2) The supply shock was large, both because of the latent demand for immigration after decades of tightly sealed borders and because of the sudden collapse of the Soviet economy (Ganguli, 2010).

(3) Neither Soviet nor American mathematicians anticipated the abrupt opening of borders due to the lifting of the Iron Curtain, so that decisions made prior to 1992 to specialize in specific areas can be viewed as exogenous.

(4) The Soviet mathematical community was not as broad as its American counterpart; further, it excelled in specific areas due to path-dependence in Soviet mathematical insights and the relatively infrequent contact between Soviet and Western mathematicians during the decades of Soviet communist rule.

(5) The supply shock resulting from the collapse of the Soviet Union was “unbalanced” in that it increased the supply of American mathematicians working in different fields differentially; some American mathematicians were highly “exposed” to the Soviet influx, while other American mathematicians barely noticed the ripples of the shock.

As a result, the post-1992 influx of Soviet mathematicians into the United States provides a unique opportunity to observe how native knowledge producers respond to new talent that suddenly chose to locate close to them in the space of ideas. Around 1992, some American mathematicians faced an influx of new intellectual colleagues and competitors, while other American mathematicians did not. Our empirical strategy is to compare the degree of intellectual mobility experienced by these two groups of American mathematicians both before and after the shock.

It is important to emphasize that although the field distribution of *actual* Soviet émigrés to the United States was selected in part due to American demand for specific types of mathematicians at that time, the historical context suggests that the distribution of all Soviet mathematicians across fields before 1992 was not related to U.S. demand. Thus, a key feature of the empirical strategy is its use of the *potential* supply shock across areas of knowledge, measured by the pre-1992 Soviet distribution of mathematicians across the fields of mathematics.

The most comprehensive data available on the published contributions of individual mathematicians (both in the United States and abroad) is contained in the American Mathematical Society’s (AMS) *MathSciNet* archives. The AMS gave us access to the information in this archive and provided us with a database that reports the number of papers published by *every* mathematician in the world, by field and year, since 1939. In

addition to the information on the number of papers, the AMS data reports the mathematician's institutional affiliation at the time the paper was published, as well as the location of the affiliation. The AMS, however, only began to collect the affiliation information on a systematic basis around 1984, so that affiliation and location are not typically available for earlier papers. Most important, the AMS professional staff assigns each publication in mathematics to one of the many fields that make up the study of mathematics. The AMS provided us with the author-year-field information at the two-digit field level, classifying every publication by each mathematician into one of 63 different fields.

Borjas and Doran (2012) used these data, combined with information from the Thomson Reuters' Institute for Scientific Information (ISI) Web of Science archive and data from the Mathematical Genealogy Project (MGP), to construct the universe of active American mathematicians prior to the collapse of the Soviet Union. In general terms, Borjas and Doran (2012) defined the population of active American mathematicians as composed of persons who, prior to 1989, had published predominantly using an American affiliation, or who, in the absence of any affiliation data, obtained their doctoral degree from an American institution.

The empirical analysis reported below will also use the sample of American mathematicians who first entered research activity after 1990. We apply the definitions introduced in Borjas and Doran (2012) to construct the more recent cohorts of American mathematicians. In particular, we examine the location of the affiliations reported in the papers published in the first five years of a mathematician's career, and classify the person

as “American” if more than half of those publications used an American affiliation. The Data Appendix contains a detailed description of the data and the construction of the samples.

We construct a panel where an observation is a mathematician/paper combination. For each mathematician/paper, we know both the paper’s two-digit field and the paper’s year of publication. In short, our data describes the entire publication history of American mathematicians between 1940 and 2009. Table 1 provides some summary statistics of the dataset. It contains a total of 711,497 published papers written by 78,684 unique American mathematicians, and about 44 percent of these mathematicians entered active research activity before 1992.

We wish to examine the trends in the field distribution of papers published by American mathematicians. Table 2 illustrates the dramatic differences in specializations between Soviet and American mathematics prior to the collapse of the Soviet Union. In particular, the table reports the “top ten” fields in the Soviet Union between 1984 and 1989, ranked by the share of Soviet papers in that field. The top two Soviet fields are Partial and Ordinary Differential Equations, and these two fields account for almost 18 percent of all Soviet publications. In contrast, only about 5 percent of American papers written during the period were in those two fields. More generally, the top five fields listed in Table 1 account for 35.6 percent of all Soviet publications, but only about 19.1 percent of American publications, while the top ten fields account for 53.2 percent of all Soviet publications and 36.5 percent of American publications.

To reduce the dimensionality of field choice from the 63 potential outcomes, we construct two alternative indices measuring the “Soviet-ness” of a particular mathematician’s research interests at a point in time. In particular, for each paper written

by an American mathematician, we construct a dummy variable indicating if the paper is in a “Soviet field”—i.e., the paper is in one of the ten fields listed in Table 1.¹⁰

To demonstrate the robustness of the results, we also use an alternative measure given by the similarity index between the research interests of a particular American mathematician and the pre-1990 Soviet field distribution. In general, let a_{if} be the share of papers that American mathematician i published in field f , and let s_f be the share of all Soviet papers published in field f before the collapse of the Soviet Union.¹¹ The index of similarity is defined by:

$$(9) \quad D_i = 1 - \frac{1}{2} \sum_f |a_{if} - s_f|.$$

The index of similarity has a number of interesting mathematical properties that make it valuable in the current context. Note that the index D_i equals one when there is a perfect overlap in the relative field distributions between American mathematician i and the Soviet research program, and zero when there is total dissimilarity. We calculate the value of the similarity index for *every* paper written by an American mathematician. It is easy to show that the value of the index of similarity for paper n written by mathematician i in field f is given by:

$$(10) \quad D_{if}(n) = s_f$$

¹⁰ We replicated our empirical analysis using alternative definitions of “Soviet fields”, including the Top 5, Top 15 or Top 20 fields, as well as subsets of these fields where American publications were relatively rare. Our empirical results are not sensitive to these alternative definitions.

¹¹ The Soviet share s_f is obtained directly from *MathSciNet* (an online database maintained by the American Mathematical Society) and contains papers published mainly between 1984 and 1989. As noted above, the AMS began to collect systematic information on the country of publication only around 1984 (although a few pre-1984 papers report the affiliation of the author).

The index of similarity for a particular paper, therefore, is simply the value of the Soviet share of the field associated with that particular paper.

Table 1 also reports summary statistics for the two measures of a paper's "closeness" to the Soviet research program. The summary data suggest a decline in the number of Soviet-style papers published after 1992. In particular, the fraction of Soviet-style papers written by the pre-existing group of American mathematicians declined from 33.4 percent for papers published before 1992 to 31.6 percent for papers published after 1992. New entrants into the mathematics market also became less likely to write papers in Soviet-style fields. The table reports the indices for the first paper published by a mathematician in his career, which we will call the "dissertation" paper. Those trends are revealing: 32.0 percent of dissertations written prior to 1992 were in Soviet-style topics, as compared to only 25.1 percent of dissertations written after 1992.

IV. The Determinants of Intellectual Mobility

Suppose that each of the 63 fields of mathematics represents a specific location in the space of ideas. While writing a paper in one of these fields, a mathematician resides in that location in idea space. After the mathematician completes a particular paper, he begins a "preparation spell" that ends when the subsequent paper is published.

During the preparation spell, a mathematician considers the benefits and costs of staying in the particular research area. This calculation may induce the mathematician to remain in the same location in idea space, or to choose a new location. A supply shock of new mathematicians into a subset of locations in idea space alters the cost-benefit calculus. Since citation rates in mathematics are far higher within each subject than across subjects,

it is clear that mathematicians make extensive use of the ideas of each other within each field.¹² Thus the increase in the stock of knowledge in that particular location in idea space resulting from the supply shock could increase productivity for mathematicians already residing in that location. But the supply shock may also increase the costs of staying in that location in idea space: other mathematicians can be competitors for resources and attention in that field. Equally important, the mathematician recognizes that intellectual mobility is costly: the length of the preparation spell may be longer if he must learn a new set of skills and mathematical techniques when moving to a different point in idea space.

This section examines two related questions. First, which factors make a mathematician decide to move to a different location in idea space in response to a supply shock? Second, does the intellectual mobility tend to represent a movement towards the research questions favored by newcomers or away from them? As the model presented in Section II showed, the net change in the relative marginal product that a mathematician faces in two potential locations in idea space depends on the relative strengths of human capital spillovers and the increased competition implied by the law of diminishing returns. The direction of intellectual mobility provides information about which of these two effects is stronger.

We begin to address these questions by examining the locational choices in idea space for the group of American mathematicians who entered active research activity *prior* to 1992. We define two distinct groups of pre-existing American mathematicians: those whose pre-1992 dissertation was on a Soviet-style topic, and those whose pre-1992

¹² See Borjas and Doran (2012), p. 1169.

dissertation was not.¹³ This simple approach exploits the fact that the pre-existing mathematicians chose their dissertation topics without considering any potential costs or benefits arising from future competition or collaboration with Soviet mathematicians.

The challenge in empirically measuring intellectual mobility is that mathematicians sometimes alternate the topics that they work on from paper to paper. We need a measure of intellectual mobility that does not interpret a regular vacillation between Field #7 and Field #32 on a set of consecutive papers as a set of fast paced intellectual journeys between these subjects; it is more likely that this vacillation itself represents the mathematician's constant "location" in the space of ideas.

We thus consider two conceptually distinct ways to measure a change in location in the space of ideas. First, we can observe whether each of the mathematician's future papers is in the same area as the dissertation topic, and measure how the probability of writing in one's dissertation area changes over time—and particularly how it changes after the Soviet supply shock. This approach is akin to thinking of a mathematician's "location" in the space of ideas as the probability distribution of that mathematician's output across fields. For simplicity, we reduce the dimensionality of the measurement by dividing fields into two categories (Soviet- and American-style). We further simplify the measurement problem by measuring all changes relative to the field of your dissertation.

¹³ Throughout the paper, we use the term "dissertation" to refer to the first paper published in a mathematician's career. We use the dissertation to define the groups of Soviet- and American-style mathematicians for two distinct reasons. First, the dissertation topic reflects the training acquired over a multi-year period that presumably prepared the mathematician for the research concerns he intended to pursue after receiving his doctorate. Second, we define the extent of intellectual mobility by using the field of each paper (*after* the dissertation paper) published over the mathematician's career. In order to avoid selecting on the dependent variable, we must exclude from our regressions any papers used to define our subgroups. The definition of the subgroups according to the field of the first published paper implies that our regressions exclude as few papers as possible. Our results are robust to using additional papers (e.g., papers published in the first 2 or 5 years) to define the subgroups of mathematicians.

Alternatively, we can measure intellectual mobility by observing the *first time* that a mathematician ever publishes in a specific field. We can measure the probability that mathematicians write for the first time in a new area that they have never worked in before, and again observe how this probability evolves over time, and particularly in the post-shock period. This measure is obviously not identical to the measure described in the previous paragraph; even if the distribution of papers across subjects does not change appreciably, the tendency to explore a brand-new area may (or many not) change a great deal over time.

As noted above, we reduce the dimensionality of locations in idea space by compressing the 63 fields of mathematics into two categories: (1) Soviet-style fields, composed of the 10 fields that were the most populated in the Soviet Union prior to the collapse; and (2) American-style fields, the residual group of the 53 other fields.

Using this simple two-way classification, we plot our first measure of intellectual mobility: the probability that a paper written in year t is in a different field than the dissertation, in the top panel of Figure 1. In the 1980s, before the collapse of the Soviet Union, American mathematicians who wrote their dissertations on American-style topics had an average probability of about 20 percent of writing in a Soviet field in later papers. This probability remained roughly constant after the Soviet influx; in fact, if anything, there is a slight decline after 1992. The evidence thus suggests that the supply shock either had no impact or a small negative impact on the propensity for intellectual mobility among mathematicians who began their career in American-style fields. In terms of the model, it seems that for these mathematicians the mobility costs of locating in a different point in idea space far exceed any positive spillover effects.

In contrast, before the collapse of the Soviet Union, American mathematicians who wrote their dissertations on Soviet-style topics had a 30 to 35 percent probability of writing on a non-Soviet topic in each of their later papers. But this probability began to increase rapidly after the Soviet influx, reaching a peak of about 50 percent by 2005. The data thus suggests that the supply shock substantially increased the propensity for intellectual mobility among American mathematicians who wrote their dissertation in Soviet-style topics. Put differently, the data strikingly show that American mathematicians who started their careers in a location in idea space that received a large number of Soviet émigrés responded to the influx by moving to a new location that received fewer immigrants. In terms of the model, the direction of the flow of intellectual movers implies that the net spillover effect must be strongly negative since it must outweigh the mobility costs.

Panel B of Figure 1 plots the residual probability of entering a field different from the dissertation after controlling for a mathematician's experience (introduced as a fourth-order polynomial) and individual fixed effects. It is again clear that within a few years after the start of the Soviet influx, there was a disproportionate increase in the tendency of American mathematicians who wrote a Soviet-style dissertation to explore an American-style research area. A comparison of the two panels of Figure 1 suggests that differences in experience profiles or idiosyncratic individual tendencies do not account for the different post-1992 trends observed in the raw data. If anything, Panel B suggests that there was an *exponential* increase in the probability that a Soviet-style mathematician would write an American-style paper after 1992.

Panels C and D of Figure 1 illustrate the trends using our second measure of intellectual mobility, a measure that indicates whether a mathematician entered a “brand new” field in year t (i.e., a field where he had never published before). The figure clearly shows that, within a few years after the start of the Soviet influx, there was a sharp increase in the tendency of Soviet-style mathematicians to explore other (i.e., non-Soviet) research areas for the first time. In sum, all four panels of Figures 1 and 2 demonstrate a large increase in the probability of intellectual mobility, however it is measured, for Soviet-style mathematicians after the influx of Soviet émigrés.

To further examine the sensitivity of our findings to controlling for various background characteristics, we estimate the generic regression model:

$$(11) \quad p_{in}(t) = \delta_i + \delta_t + \theta(T_i \times S_i) + Z_i \beta + \varepsilon,$$

where $p_{in}(t)$ is the indicator variable of intellectual distance from the dissertation to paper n published by mathematician i in calendar year t ; T is a dummy variable indicating if that paper was published after 1992; S_i is a dummy variable indicating if the mathematician’s dissertation topic was in a Soviet-style field; Z is a set of characteristics that may influence a mathematician’s location in idea space (discussed below); and δ_i and δ_t are vectors of individual and calendar year fixed effects, respectively. It is important to emphasize that this regression model is estimated using only the sample of pre-existing American mathematicians.

Table 3 reports the relevant coefficients from this regression model using several alternative specifications. Regardless of the specification, we find that the supply shock led to a substantial increase in intellectual mobility out of Soviet-style areas and into

American-style work. Consider, for instance, the simplest specification reported in column 1, which does not include any variables in the vector Z . The coefficient of the interaction variable between the post-1992 indicator and the variable indicating whether the mathematician wrote a Soviet-style dissertation is around .12, regardless of the measure of intellectual mobility used. Put differently, the probability of moving to American-style research for Soviet-style mathematicians increased by about 12 percentage points after the supply shock.

The data also allows us to examine the question of *which* mathematicians are most likely to engage in intellectual mobility. As our model showed, intellectual mobility occurs when the net spillovers due to an influx of mathematicians into a particular location in idea space outweigh the costs of migration. As a result, the intellectual movers are a self-selected sample of mathematicians. Hence, we can examine the distinctive characteristics of this sample to learn about how the net spillovers or the mobility costs differ among groups of mathematicians.

The second column of the table includes two variables in the vector Z : an indicator of whether the mathematician was tenured as of 1992, and the log of the number of papers per year that the mathematician published prior to 1992. The individual fixed effects, of course, subsume the direct effect of both of these variables. Nevertheless, it is possible that their impact differs in the pre- and post-shock periods. The table reports the interaction of these “quality” variables with the post-1992 indicator. It is noteworthy that both of these interaction variables are negative, although only the pre-1992 rate of output is statistically significant.

A more interesting specification allows for the impact of these “quality” variables to differ not only pre- and post-shock, but also between American- and Soviet-style mathematicians. The fully interacted model presented in the third column of Table 2 reports the coefficients from this general specification.

Consider initially the variable measuring whether the mathematician was tenured at the time of the supply shock in the regression that examines intellectual mobility to a “brand new” field. The three-way interaction (post-1992 indicator \times Soviet-style dissertation \times tenured as of 1992) is strongly negative, indicating that the impact of the supply shock in driving Soviet-style mathematicians away from Soviet-style research was attenuated if the mathematician had job security at the time. Note that the numerical magnitude of this attenuation effect is large: the probability of intellectually moving for the first time to an American-style research area after the Soviet supply shock falls by 4.6 percentage points if the mathematician was tenured.

Similarly, although the inclusion of individual fixed effects controls for differences in individual quality, there may be a differential effect between high- and low-quality mathematicians. The last column of Table 2 shows that the coefficient of the three-way interaction variable (post-1992 indicator \times Soviet-style dissertation \times log rate of output) is also negative and significant, suggesting that high-quality Soviet-style mathematicians were relatively less likely to intellectually move after the supply shock.¹⁴

The numerical magnitude of the coefficient is also interesting. In particular, the impact of the Soviet supply shock on intellectual mobility switches sign from negative to

¹⁴ Both the tenure and the rate of output variable are defined to have zero mean. This implies that the “intercept” (which is the two-way interaction between the post-1992 indicator and the variable indicating if the mathematician wrote a Soviet-style dissertation) is evaluated at the mean of the quality variables.

positive when the log rate of output has a value of around 1.0.¹⁵ This threshold essentially “marks” the 90th percentile of the rate of output distribution, so that mathematicians whose rate of output prior to the shock was at least 3.7 papers per year actually prefer to stay to those locations in idea space where the Soviet émigrés cluster. Put differently, the regression analysis reveals the presence of a potentially important type of selection: the intellectual mobility effects of the supply shock are attenuated for the best Soviet mathematicians. In terms of our theoretical model, this type of selection can only occur if either the net human capital spillovers are positive and very large for the “best” Soviet-style mathematicians or if their mobility costs are relatively high.

In the next section, we consider whether intellectual mobility is correlated with any empirically verifiable costs, and how these costs vary across different groups of mathematicians, before returning to the question of why the best mathematicians have a relatively lower intellectual mobility rate in response to the Soviet supply shock.

V. The Costs Associated with Intellectual Mobility

Intellectual mobility may be costly. A mathematician may have to acquire additional technical skills that are required to prove theorems at the new location in idea space. This process takes time and may lead to a longer “preparation spell” (i.e., the amount of time that the mathematician spends preparing and marketing a new publication). It is easy to document, in fact, that preparation spells are longer if the spell involves a switch to a new field. The Soviet supply shock could then potentially increase the costs of intellectual

¹⁵ In particular, the coefficient of the two-way interaction between the post-1992 indicator and the Soviet-style dissertation is .082, while the coefficient of the three-way interaction between these two variables and the log rate of output is 0.087.

mobility in two distinct ways. First, it increased the propensity for intellectual mobility. Second, the clustering of large numbers of Soviet mathematicians in specific locations in idea space could increase the amount of preparation time required by mathematicians already residing there.

Table 3 summarizes the available evidence on the length of preparation spells for Soviet- and American-style mathematicians, before and after the supply shock. We define the duration of a preparation spell as the length of time elapsed (in years) between any two consecutive papers in a mathematician's career. Consider initially the preparation spells experienced by American-style mathematicians. Panel B of the table shows that before the supply shock, the time lag between one American-style paper and another American-style paper was 0.980 years. Nevertheless, when this American-style mathematician delved for the first time in a Soviet-style field, the duration of the preparation spell increased substantially to 2.195 years (see panel E). In other words, prior to the supply shock, it took an American-style mathematician an additional 1.22 years to prepare their first Soviet-style paper.

Consider now the group of mathematicians who wrote a Soviet-style dissertation. Panel C shows that before the supply shock, the preparation spell lasted 0.835 years if these mathematicians went from one Soviet-style paper to another. However, when a Soviet-style mathematician first tackled an American-style paper, the length of the preparation spell increased to 2.289 years. Even before the supply shock, therefore, it took a Soviet-style mathematician an additional 1.45 years to prepare the first-ever American-style paper.

In short, the evidence suggests that it may be costly to move to new locations in idea space. In fact, the observed duration of the preparation spells reported in Table 3 probably underestimate the true magnitude of this type of mobility costs. After all, the intellectual movers are a self-selected sample representing the subset of mathematicians who had either the most to gain from the move and/or the smallest mobility cost.

In addition to showing that there is a strong correlation between the length of a preparation spell and the likelihood of entering a new field, we can also use the data to determine if this correlation becomes even more pronounced after the supply shock. As the last two columns of Table 3 reveal, there seems to be one particular type of preparation spell that was extremely sensitive to the Soviet supply shock, namely the one reporting the duration of the preparation spell for Soviet style mathematicians who are preparing their first-ever American-style paper. The duration of this particular type of preparation spell increased dramatically from 2.289 years in the pre-shock period to 5.074 years after the supply shock. Put differently, instead of taking an additional 1.45 years to write their first-ever American paper, a Soviet-style mathematician took an additional 4.26 years after 1992.

We examine the sensitivity of these findings to controlling for various characteristics by estimating the regression model:

$$(12) \quad y_{in}(t) = \delta_i + \delta_t + \theta_1(T_i \times S_i) + \theta_2(T_i \times S_i \times F_{in}) \\ + \kappa_1(T_i \times A_i) + \kappa_2(T_i \times A_i \times F_{in}) + Z_i \beta + \varepsilon,$$

where $y_{in}(t)$ is the duration of the preparation spell that culminated in mathematician i publishing paper n at time t ; F_{in} is a dummy variable indicating if this particular spell culminated with the mathematician publishing a paper in a “brand-new” field (i.e., a field

that he had not previously explored); and $A_i = (1 - S_i)$. Note that the regression includes both time and individual fixed effects.

The data consists of a panel that includes the preparation spells experienced by every American *pre-existing* mathematician in our sample.¹⁶ Table 4 reports the relevant regression coefficients. Consider initially the simplest specification reported in column 1, which does not include any variables in the vector Z . The coefficients of the three-way interaction variable between the post-1992 indicator, the variable indicating whether the spell culminated in the mathematician entering a brand-new field, and the indicator of whether the mathematician is Soviet- or American-style are strongly positive and significant. The difference between the two coefficients, which is approximately around a year, indicates that our earlier conclusion based on the raw data is unaffected by the inclusion of individual and year fixed effects: Soviet-style mathematicians entering a new field had a substantial relative increase in the duration of the preparation spell after the supply shock.

The last column of the table shows that this increase is attenuated somewhat for high-quality mathematicians. As in the last section, we introduce a variable measuring the rate of output for mathematician i prior to the supply shock. The coefficients reported in the table suggest that the Soviet supply shock particularly lengthened the duration of the preparation spell for low-quality mathematicians moving to an entirely new location in idea space after 1992.

¹⁶ The regression only includes those spells that potentially allow for a change to a brand new field to occur. Once a Soviet-style (American-style) mathematician writes his first-ever American-style (Soviet-style) paper, all subsequent spells in that mathematician's career must have a "zero" for the dependent variable. We exclude all these subsequent spells from the regression.

To summarize, not only is there a correlation between the duration of the preparation spell and the propensity to enter a new field, but this correlation increased markedly after the supply shock. This observed increase in the correlation is consistent with two causal scenarios: (1) the supply shock made it relatively more difficult for Soviet-style mathematicians to produce (and/or sell) output, creating a longer down time in between publications and spurring some of them to seek a new location in idea space; or (2) the supply shock induced Soviet-style mathematicians to intellectually move; the subsequent retooling implies that it took them longer to prove their first theorems in their new location in idea space. Under the first scenario, intellectual migration does not cause time lags, but is rather caused by them. Under the second scenario, the causation is reversed. The natural experiment we exploit in this paper is not designed to distinguish these causal chains from each other. Nevertheless, the data reveal an important correlation that will likely play a role in attempts to understand the nature of the costs of intellectual mobility in future research.

Finally, it is worth asking: why did the best American mathematicians exhibit the lowest intellectual mobility rates in response to the Soviet supply shock? As we noted earlier, this correlation can be explained in two ways: the best mathematicians benefited the most from the positive spillovers generated by the expansion in the stock of mathematical ideas and/or the best mathematicians had the highest intellectual mobility costs. The results presented in this section, however, strongly suggest that the best mathematicians, in fact, tend to face relatively low costs of intellectual mobility. As a result, the evidence is most consistent with the conjecture that the beneficial human capital

spillovers resulting from the Soviet supply shock most likely accrued to the subsample of the most productive American mathematicians.

VI. The Evolution of Field Choice Over the Life Cycle

The empirical analysis has demonstrated that American mathematicians who wrote a Soviet-style dissertation were much more likely to intellectually move to research activities on American-style topics after 1992. We now examine the evolution of a mathematician's research interests over the life cycle, and how the life cycle path of research interests was disrupted by the supply shock initiated by the collapse of the Soviet Union in 1992.

It is instructive to think of two distinct ways of summarizing how the intellectual mobility documented in Section III affects the life cycle path of research choices. At time t , for example, the field composition of a mathematician's publications *in that particular year* should reflect the impact of the various moves in idea space that have taken place up to that point in the life cycle. In addition, we can also define a *cumulative* measure of a mathematician's research interests by examining the field composition of all papers that he has published up to and including time t .

We estimate a regression model that allows us to quantify the impact of the Soviet supply shock on the aging-specialization profile. We aggregated the dataset constructed earlier to the author-year unit of analysis, so that an observation represents an author-year combination. By construction, an observation for a particular mathematician exists only in those years where the mathematician has published at least one paper. We first examine a measure summarizing the field mix of papers published by the author at time t . As noted

above, the location of a mathematician in idea space at time t is the end result of all the intellectual mobility decisions made by the mathematician prior to and including time t . We wish to determine how the field mix at a particular point in time changes over the cycle, and if this aging profile was displaced by the Soviet supply shock in 1992. Let x_i denote mathematician i 's years of experience, defined as the number of years elapsed between the time the mathematician first published and time t . We estimate the regression model given by:

$$(13) \quad y_{it} = \delta_i + \delta_t + \alpha_1(x_i \times S_i) + \alpha_2(x_i \times T_i \times S_i) \\ + \beta_1(x_i \times A_i) + \beta_2(x_i \times T_i \times A_i) + \varepsilon,$$

where y_{it} is the “Soviet-ness” index for papers published by mathematician i in calendar year t . The coefficients of interest are contained in the vector $[\alpha_1, \alpha_2, \beta_1, \beta_2]$. This vector summarizes how the age-specialization profiles differ between Soviet- and American-style mathematicians, as well as before and after the Soviet supply shock. Note that the inclusion of individual and calendar year fixed effects implies that the differential impact of the shock on field choice is identified from variation within individuals (after controlling for whatever common “fads” may exist in field choice over time). We use two alternative dependent variables in this part of the analysis. The first is simply the fraction of papers that mathematician i wrote in year t that are in Soviet-style fields, and the second is the average similarity index of the papers published in that year.

We estimate equation (13) by defining experience as a fourth-degree polynomial. The vector of coefficients of interest, therefore, is not easy to interpret (but the coefficients

are reported in Appendix Table A-1). The results are much easier to understand by tracing out the age-specialization profiles implied by the estimated coefficients. Panels A and B of Figure 2 illustrate how the age profiles differ among the four groups of interest.¹⁷

It is evident that the different rates of intellectual mobility between American- and Soviet-style mathematicians before and after the Soviet supply shock create significant differences between their age-specialization profiles as well. Both panels suggest that the age profile of American-style mathematicians was roughly the same before and after 1992, although there is a tendency for the American-style mathematicians to publish fewer Soviet papers at a given level of experience after 1992. The figure also illustrates, however, a dramatic difference in the age-specialization profile of Soviet-style mathematicians before and after the shock. In particular, the probability that a Soviet-style mathematician published a Soviet-style paper in the 20th year of experience fell by about 10 percentage points after the shock.

In addition to the impact of prior intellectual mobility decisions on the field mix of papers published at time t , it is also interesting to examine the *cumulative* impact of the various moves in idea space on the field mix of a mathematician's entire life *oeuvre*. In particular, what fraction of all the papers that a mathematician has published by the time he has x years of experience are in Soviet-style fields, and how was this cumulative summary measure affected by the Soviet supply shock?

We re-estimated the regression model in (13) using a dependent variable that gives the fraction of papers published *by* year t that conduct Soviet-style research. Panel C of

¹⁷ The predicted specialization rates are normalized to equal zero for all groups at the beginning of the life cycle.

Figure 2 illustrates the age-specialization profiles implied by the estimated coefficients. Not surprisingly, the cumulative impact of the shock dampens the growth that would have otherwise occurred among American-style mathematicians in the fraction of a mathematician's cumulative work that dabbled in Soviet-style topics. In other words, for American-style mathematicians, the evidence suggests that the Soviet supply shock *reduced* the degree of intellectual diversity in their life *oeuvre* because it reduced incentives to dabble in Soviet-style topics. In contrast, Figure 4 shows a strong reduction in the fraction of cumulative papers that involve Soviet-style research for mathematicians who started out with a Soviet-style dissertation. Put differently, the supply shock *increased* the degree of intellectual diversity that Soviet-style mathematicians experienced over their life cycle because it increased the incentives to dabble in American-style fields.

Finally, up to this point our analysis has focused exclusively on the two-way classification of fields into Soviet- and American- style fields. One easy way to determine the robustness of the evidence from a different perspective is simply to calculate an independent measure of intellectual diversity that does not rely in any way on a classification of Soviet- and American-style fields. We define a new dependent variable giving the cumulative log number of fields in which a mathematician has published by the time he has x years of experience, where the fields are defined in terms of the original 63 fields available in the AMS data. The larger the number of fields that a particular mathematician has published in by the time he has acquired x years of experience, the greater the degree of intellectual diversity that the mathematician has shown in his published work over the life cycle. We re-estimated the regression model in equation (13)

using this alternative dependent variable, and the implied age-specialization profiles are illustrated in Panel D of Figure 2.

It is evident that the log number of fields increases over the life cycle for all mathematicians—regardless of whether the dissertation was in a Soviet- or American-style or field, and regardless of whether the mathematician’s life cycle is observed before or after the Soviet supply shock. Nevertheless, the Soviet supply shock had a particularly strong positive impact on the lifetime intellectual diversity exhibited by Soviet-style mathematicians. After 20 years of experience, the supply shock likely increased the total number of fields in which a Soviet-style mathematician had published by about 5 percentage points.

VII. Field Choices of New Cohorts

Up to this point, the analysis has examined the intellectual mobility response among “pre-existing” American mathematicians to the economic forces unleashed by the collapse of the Soviet Union, and the subsequent diffusion of Soviet mathematicians and Soviet ideas after 1992. The empirical evidence unambiguously suggests that the competitive pressures arising from a new abundance of Soviet-type mathematicians led many pre-existing mathematicians to switch away from those fields.

Obviously, the same economic forces will likely influence field choices for new entrants into the American mathematics market. Graduate students, as they prepare their dissertation and invest in the skills required to become specialists in their chosen fields, will inevitably consider the long-term value of the various options available, and will make a decision based not only on the suitability of the match between their specific skills and

the technical requirements of particular fields, but also on the marketability of research in specific fields. The trend in the number of new mathematicians choosing to specialize in Soviet fields would then provide independent evidence on the relative importance of competitive versus spillover effects. Fewer new American mathematicians will choose to produce a Soviet-style dissertation if competitive forces dominate, while many more new mathematicians would produce Soviet-style dissertations if the productivity gains resulting from the Soviet supply shock are substantial.

We illustrate the nature of these “cohort effects” by examining the field choice of the first paper published by each mathematician. As before, we call this field choice the dissertation field.¹⁸ The two panels of Figure 3 illustrates the trend in the cohort effects among American mathematicians who first published between 1978 and 2009, using both the probability that the dissertation is in a Soviet-style field and the similarity index. Panel A shows that the fraction of American dissertations in Soviet-style fields was relatively stable from 1978 through the late 1980s. In 1978, for example, 32.3 percent of American dissertations were in Soviet-style fields; by 1989, the respective fraction was 32.7 percent. Beginning around 1990, however, however, the relative number of Soviet-style dissertations produced by new American mathematicians began to decline, and this decline continued steadily through 2007. In 2007, for example, only about 22 percent of the dissertations produced by new American mathematicians were in Soviet-related fields.

It is tempting, of course, to attribute the steep post-1990 decline in the relative number of Soviet-style dissertations to the competitive forces that we have emphasized

¹⁸ We replicated the analysis presented in this section using alternative definitions of the “first” choice, including papers published in the first year, in the first five years, or in the first ten years, and the cohort trends are quite similar.

throughout the analysis. Before such a conclusion can be reached, however, it is important to emphasize that there are “period effects” in dissertation topics that may account for the trends in the field composition of American dissertations illustrated in Figure 3. Newly minted researchers are not immune to fads, and the trend in the field composition of American dissertations in mathematics may well be reflecting *global* fads in the profession.

It is important, therefore, to contrast the trends in the field choices made by new American mathematicians to the field choices made by mathematicians in a control group, a group of mathematicians where we could isolate the period effects introduced by the changing fads. One potential control group could be the group of mathematicians in the “rest of the world” (excluding the Soviet Union).¹⁹ The two panels of Figure 3 also illustrate the trend in the field mix index of dissertations written by this group of mathematicians. The data clearly show that the “Soviet-ness” index is much more stable in the control group than among American mathematicians. In fact, the figure implies a difference-in-differences estimate of between 5 to 10 percentage points in the fraction of American dissertations that explore Soviet-style topics after 1992.

An obvious problem with the choice of the group of mathematicians residing abroad as a control group is that many of these mathematicians may have been affected by the collapse of the Soviet Union in two distinct ways. A direct effect arises simply because about two-thirds of the Soviet émigrés eventually settled in countries other than the United States, so that many of these non-American mathematicians faced direct labor market competition similar to that experienced by American mathematicians.

¹⁹ See the Data Appendix for a detailed description of how this group of mathematicians was constructed.

In addition, a number of indirect effects likely contaminate the baseline trend in the relative number of Soviet-style dissertations produced abroad. In particular, many of the mathematicians residing outside the United States compete directly with American mathematicians for publication space in the main journals. After 1992, this competition would be increasingly harsh for foreign mathematicians working in Soviet-style research topics, and hence we could expect to observe a decline in the number of new foreign mathematicians who wish to specialize in Soviet-style topics. Similarly, there could be diffusion effects through the geographic migration of mathematicians trained in one country, but obtaining jobs in another. For example, some of the American-trained Soviet-style mathematicians may have been unable to secure permanent jobs in the United States, and diffused the “local” impact of the Soviet influx to other countries, even countries that did not receive any Soviet émigrés after 1992.²⁰

One way to reduce the importance of these contaminating forces would be to examine a subset of mathematicians residing outside the United States, but living in countries that received relatively few Soviet émigrés (defined as countries where the Soviet émigrés made up less than a 0.5 percent increase in the size of the mathematics workforce).²¹ Figure 3 also summarizes the “Soviet-ness” trends made by new cohorts of mathematicians in this subset of countries. This trend can only be calculated for the 1984-2009 period due to data limitations. The figure reveals that the trend in this subset of “unaffected” countries closely mirrors the worldwide trend outside the United States.

²⁰ In fact, if the diffusion effects were very strong, there would not be a discernable difference in the relative number of Soviet-style dissertations produced in the United States and abroad.

²¹ The list of the “unaffected” countries is drawn from Borjas and Doran (2012), Table IX.

Table 6 reports a regression analysis showing the magnitude of the cohort effects in the United States relative to those observed in the two potential control groups. In the first two columns of the table, the sample consists of all dissertations written by American mathematicians and by the respective control group. The dependent variable is an index of the “Soviet-ness” of a particular dissertation. It is evident that new entrants in the American mathematics market wrote many fewer Soviet-style dissertations after 1992 than either mathematicians in the “rest of the world” or than mathematicians residing in the subset of unaffected countries. In particular, the fraction of American dissertations published after 1992 in Soviet-style topics declined by 5.5 percent relative to those published in the rest of the world, and by 6.1 percent relative to those published by mathematicians in unaffected countries.

Finally, the last column of Table 6 examines an interesting aspect of the decline in the fraction of American dissertations written in Soviet-style topics. As we have seen repeatedly, the competitive effects induced by the Soviet influx tend to be attenuated for “high-quality” mathematicians. It would be of interest to determine if a person’s innate productivity also influences the field choice made at the dissertation stage, and attenuates the cohort effects documented in this section.

We have few socioeconomic background variables that may provide a hint about the person’s overall quality at the time of the dissertation. However, a select group of American mathematicians (about 16.7 percent) entered the labor market with a “splash.” In particular, they published more than one paper in their entry year. We define an indicator variable set to unity indicating whether the mathematician made a “high-volume” entry into the mathematics profession and estimate a regression model to determine if the

cohort effects are similar among these prolific publishers. As the regressions show, these prolific American mathematicians were around 5.4 percent more likely to produce a Soviet-style dissertation prior to 1992, and this gap actually increased after 1992 by an additional 3.3 percentage points.²² As with our earlier results, to the extent that high-quality mathematicians are particularly susceptible to the benefits generated by human capital spillovers, the evidence indicates that these spillovers may have had an important effect on the dissertation choice of this select group after 1992.²³

VIII. Summary

Economists have found that geographic mobility, occupational mobility, and job mobility are all important mechanisms that the labor market uses to adapt to supply and demand shocks. This paper introduces the notion of intellectual mobility as a key equilibrating mechanism in the market for knowledge production.

We examined empirically the labor supply shock that occurred in the space of mathematical ideas in the United States after the collapse of Soviet communism. Our analysis exploits the fact that the influx of Soviet mathematicians into the American mathematics community was clustered in a relatively small number of fields. The unbalanced nature of the supply shock across locations in idea space allows us to observe the flows of intellectual mobility unleashed by the changed economic opportunities resulting from the supply shock.

²² We also have information about the university where American mathematicians obtained their doctoral degree for about half of the American sample. We estimated some specifications that included a school-quality variable, but the results were not robust likely because of the sample selection.

²³ Note also that the initial field choice at the dissertation stage is not influenced by the mobility costs that must be incurred when moving from one location to another in the space of ideas.

We constructed several empirical measures of intellectual mobility. Regardless of the measure, we document that the diminishing returns to specific research areas resulting from the increase in supply dominated the intellectual mobility decisions of pre-existing knowledge producers. This finding extends to new cohorts of mathematicians who entered the marketplace after the Soviet supply shock. The new cohorts increasingly chose dissertation topics that had experienced a relatively small increase in supply from the Soviet émigrés. In general, therefore, the evidence is clear: the Soviet supply shock led to intellectual mobility flows that drove American mathematicians away from those locations in idea space that received large numbers of Soviet émigrés.

Our analysis also begins to shed light into the black box of the intellectual mobility decision by delineating some of its determinants. We consistently observe that high-quality mathematicians were less likely to move to a different location in the space of ideas in response to the Soviet supply shock. Framing the question in terms of a simple Roy-type model of intellectual mobility, this evidence is consistent with the conjecture that high quality mathematicians either have higher costs of movement or more positive net spillovers to interaction with other knowledge producers.

While the literature on the determinants and consequences of intellectual mobility is at its infancy, the evidence reported in this paper demonstrates that the flow of knowledge that an economy can produce depends intimately on the decisions of knowledge workers to change their location in the space of ideas throughout their life-cycle, and that these decisions are themselves a function of supply (and demand) shocks. We suspect that further study of the determinants and consequences of intellectual mobility may lead to a

greater understanding of knowledge spillovers, the knowledge production function, and the long-term impact of high-skill immigration on economic growth.

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Data Appendix

The data used to construct our dependent and independent variables are drawn from a single database: the universe of publications in mathematics as archived by the American Mathematical Society (AMS) *Mathematical Reviews*. In order to define a sample of “American” mathematicians who were active in the American mathematical market before 1984, we also use data drawn from two additional databases: the Thomson Reuters’ ISI Web of Science archive; and the Mathematical Genealogy Project (MGP) data that links new doctoral degrees granted in mathematics to their doctoral advisors.

1. AMS *Mathematical Reviews*

AMS *Mathematical Reviews* records the titles, publication sources, author names, references, fields, and citations of over 2 million articles from 2,764 different journals and publication sources worldwide. The editors of *Mathematical Reviews* also record subject classification codes for each paper in its database: 64 subfields defined according to the 2-digit 2010 Mathematics Subject Classification (MSC2010), 104 subfields (3-digit MSC), or 610 subfields (5-digit MSC). We use the 2-digit coding throughout. Beginning in the early 1980s, the archival record of each published paper provides information not only on the author and the field of the paper, but also on the author’s affiliation at the time the paper was published.

The AMS provided us with a spreadsheet containing the publication history of all mathematicians since 1939. A row in this spreadsheet defines a particular permutation of author (i), field (j), and year (t). For each (i, j, t) row we have information on: the number of papers published; the institutional affiliation(s) associated with the papers in that row; and the (country) location of the affiliation(s).

2. Thomson Reuters’ ISI Web of Science

The ISI Web of Science records the titles, publication source, author names, references, and citations of millions of articles from thousands of journals worldwide. For many articles (especially after 1978), the database records research addresses and reprint addresses for each author. We purchased the records of all 1.2 million articles in the primary ISI Web of Science database between 1970 and 2009 for the following categories: Mathematics, Applied Mathematics, Interdisciplinary Applications of Mathematics, Mathematical Physics, and Statistics & Probability. We also purchased the records of all 1.9 million articles referenced by these main articles, and the 2.4 million papers that cite these main articles. We obtained special permission from the AMS to merge our ISI papers by title, source, and author with the AMS database. The variables analyzed in this paper are not drawn from the matched sample. The ISI data are used to simply gather location information (between 1978 and 1984) for mathematicians who do not report any post-1984 location in the AMS database.

3. Mathematics Genealogy Project (MGP)

For doctoral degrees awarded in mathematics, the MGP database reports the name of the degree recipient, the name of the doctoral advisor, the year in which the degree was completed, and the name of the institution granting the degree. In addition to these data, the MGP also provided us with each advisor’s and student’s AMS unique author identifier.

The identifier allows us to merge MGP database with the AMS/ISI databases, and obtain all the available information on the publication and citation records of both students and advisors. The unique AMS identifiers are available for about 65 percent of degrees awarded since 1960.

4. Construction of the sample of predominantly American mathematicians

We focus on a sample of mathematicians whose first published paper occurred on or after 1940. The database provided to us by the AMS reports the mathematician's institutional affiliation and location for any year that the mathematician published at least one paper. In Borjas and Doran (2012), we used the AMS data to identify the number of times that the reported institutional affiliation prior to 1989 was located in the United States. We supplemented the information available in the AMS data by using both the ISI and the MGP data to define the sample of predominantly American mathematicians. As noted above, the ISI data contains affiliation and location information for many other published papers between 1978 and 1983. We use this location information if the equivalent post-1984 data are not available in the AMS. Finally, the MGP database reports the institution where the mathematician received the doctoral degree. A mathematician is then classified as "predominantly American" if the AMS/ISI location data indicate that more than half of the affiliations of publication prior to 1989 were located in the United States. If the pooled AMS/ISI data do not provide any information on the location of the mathematician prior to 1989, we assume that a mathematician who received a doctoral degree in the United States between 1950 and 1977 is affiliated with an American institution and he, too, is classified as predominantly American.

We employed this approach to define the sample of predominantly American mathematicians who first published after 1989. In particular, we examined the affiliation data in the AMS available for papers published in the first five years of the career, and classify a person as predominantly American if more than half of the papers published in that interval used an American affiliation. We used a similar approach to define the baseline sample of non-American mathematicians used in the cohort analysis reported in Section VII.

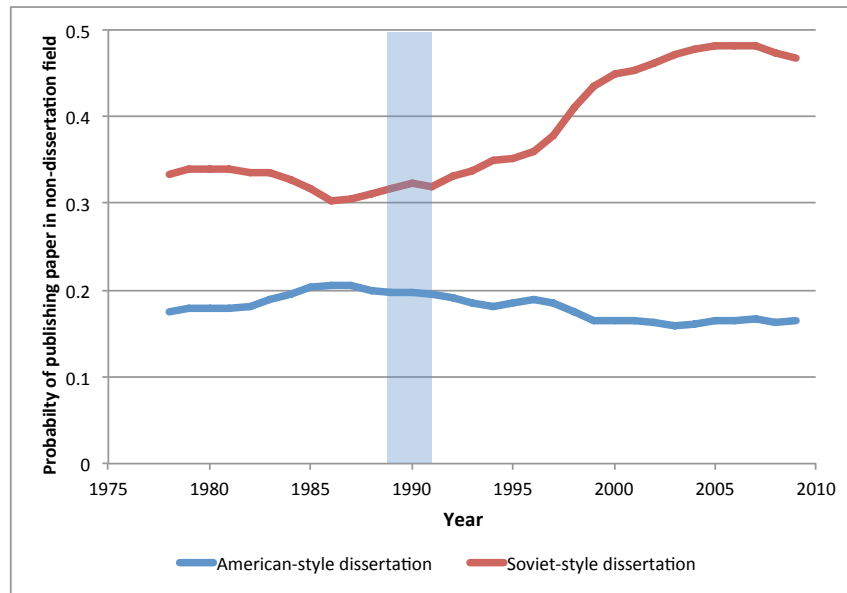
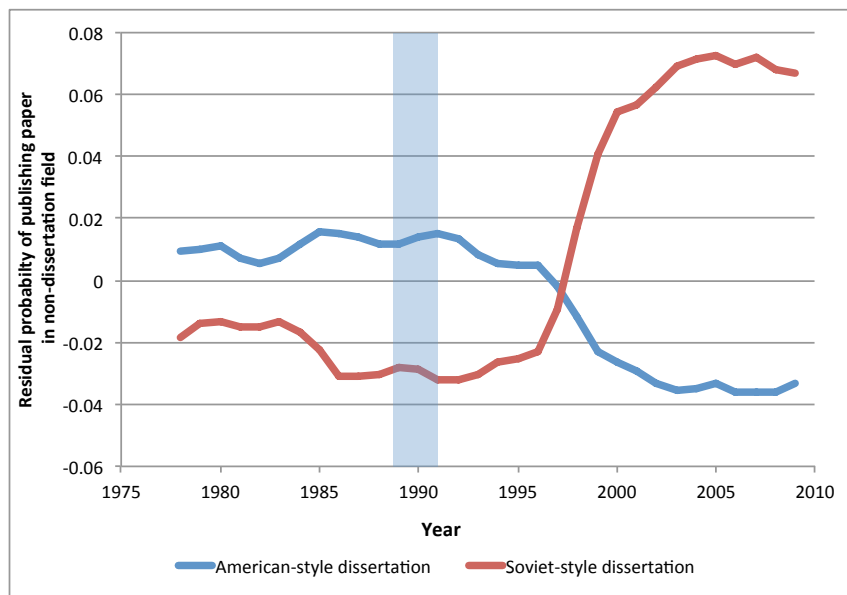
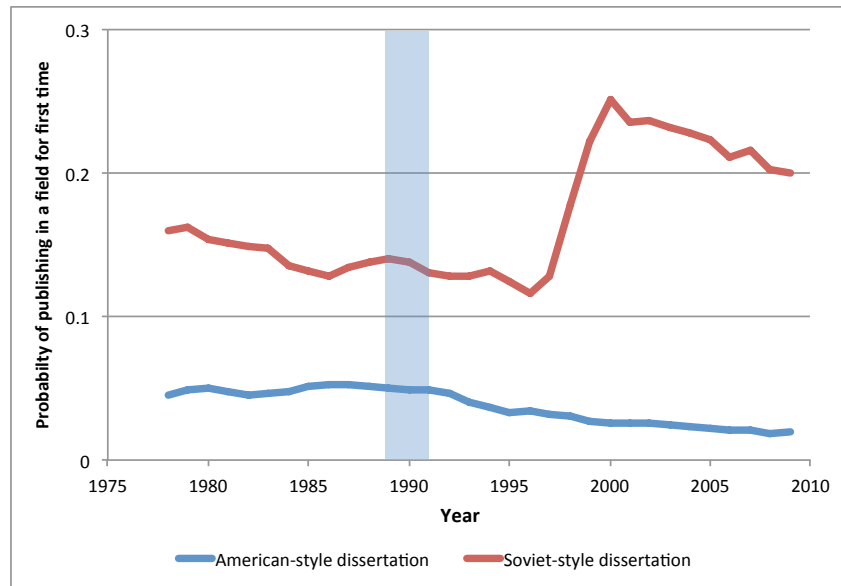
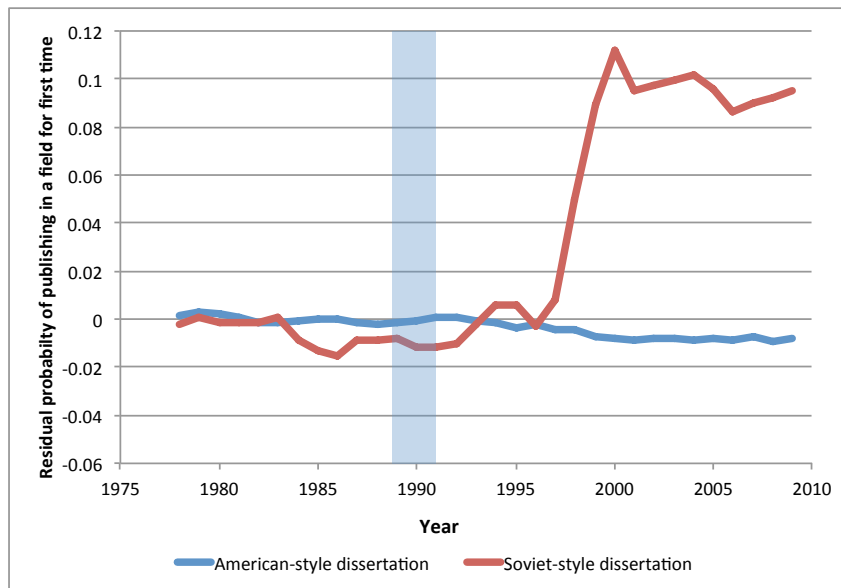
Figure 1: Trends in Intellectual mobility, 1978-2009**A. Probability of publishing in a field different from dissertation****B. Residual probability of publishing in a field different from dissertation**

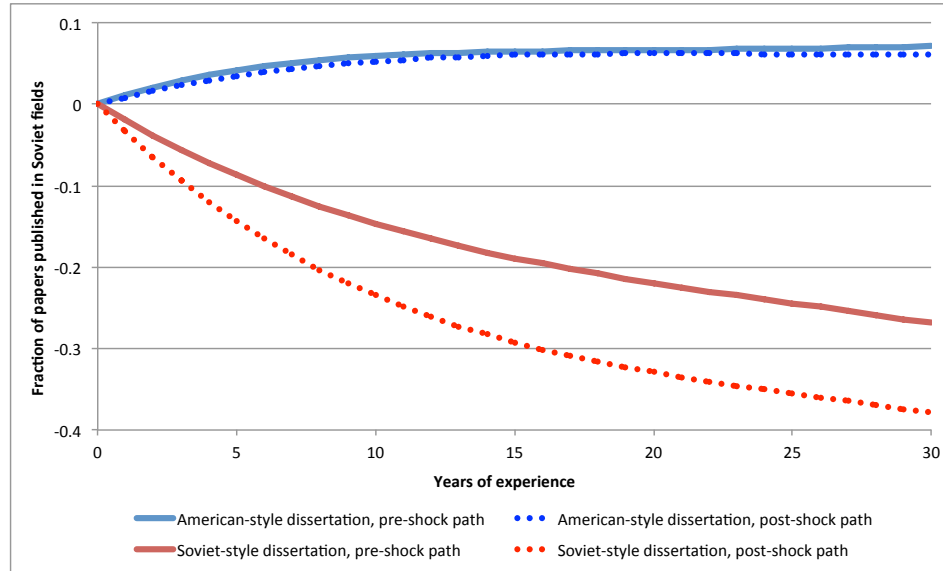
Figure 1, continued

C. Probability of publishing in a brand new field**D. Residual probability of publishing in a brand new field**

Notes: The sample consists of American mathematicians who first published before 1992. See Table 1 for the list of fields that are Soviet-style; all other fields, by definition, are American-style. The residual rate of intellectual mobility is the average residual from a regression estimated at the author/paper level where the regressors include a quartic in experience and a vector of individual fixed effects. We smooth out the trend by using a 3-year moving average of the rate of intellectual mobility centered around the middle year in the interval.

Figure 2: The evolution of field specialization over the life cycle

A. Fraction of papers that are in Soviet-style fields at time t



B. Similarity index with Soviet field distribution at time t

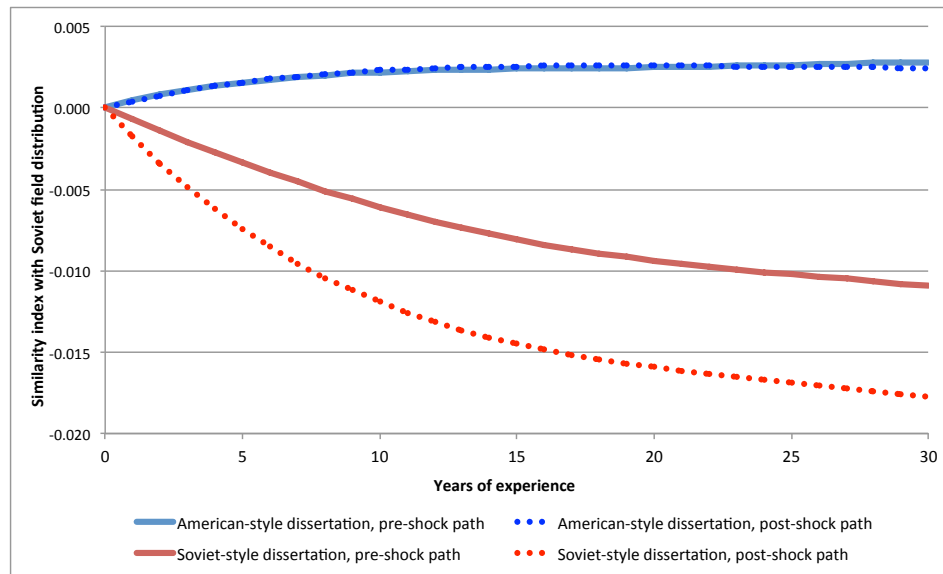
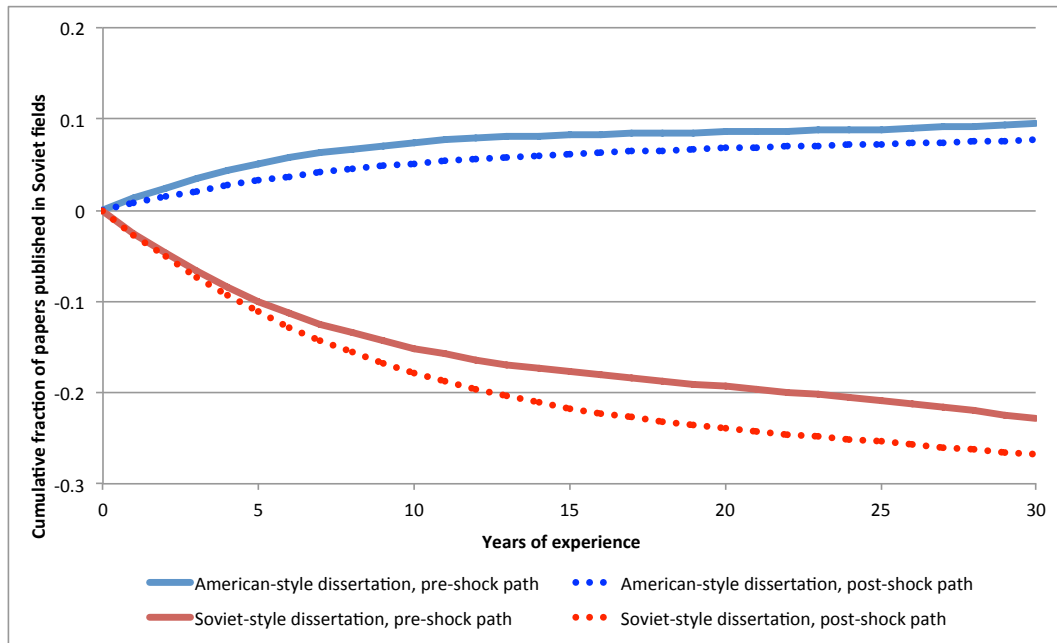
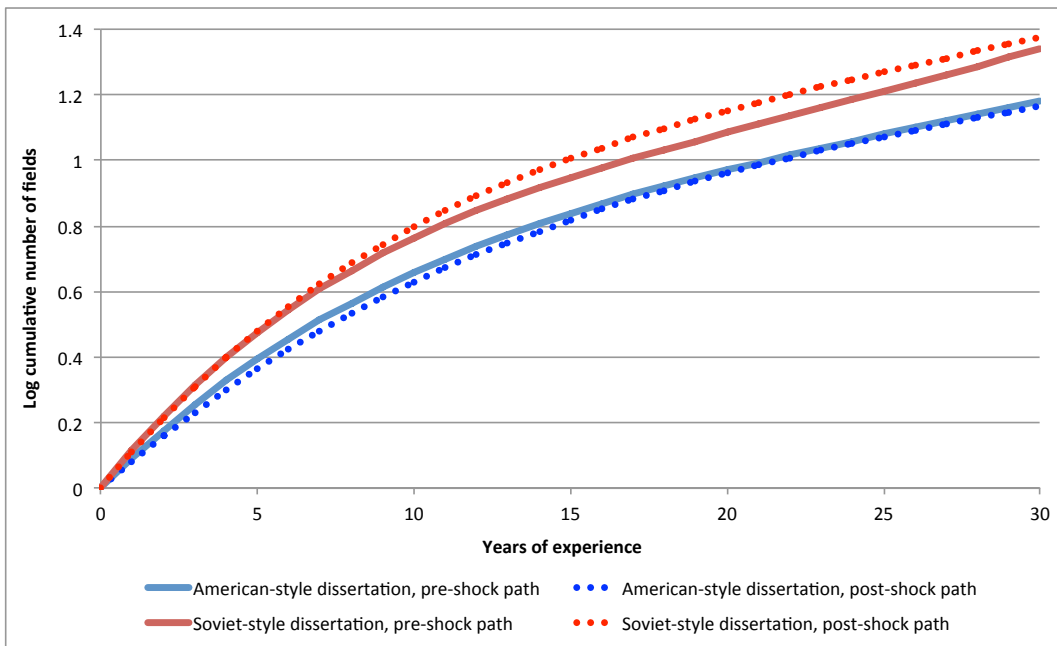
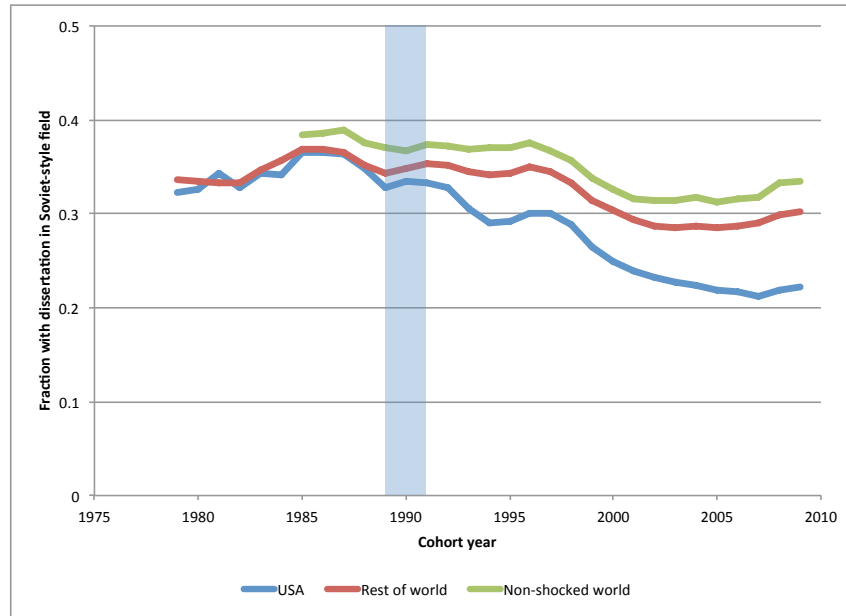
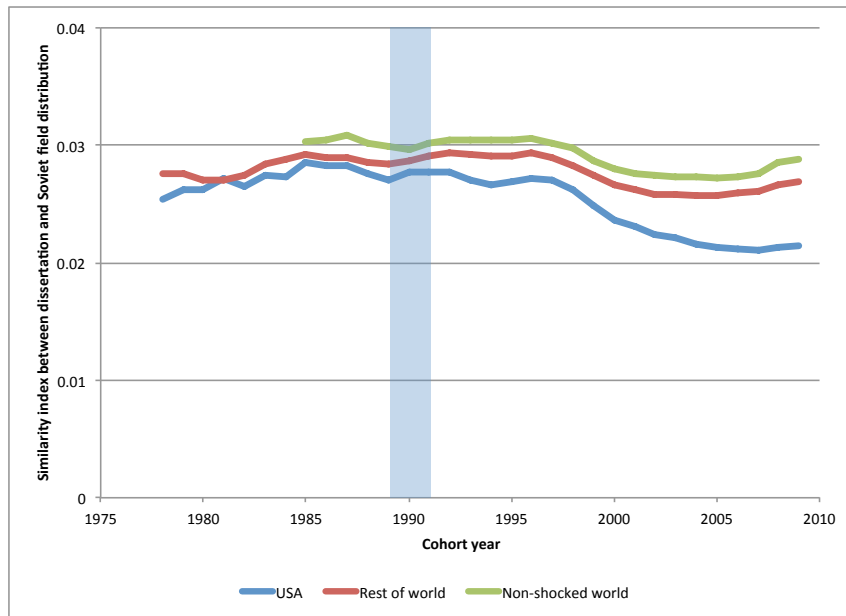


Figure 2, continued.

C. Fraction of papers published in Soviet fields up to time t **D. Log number of fields up to time t** 

Notes: The sample consists of American mathematicians who first published before 1992. The age-specialization profiles are predicted using the regression model in equation (13); the estimated life cycle profiles are reported in Appendix Table A-1. The sample consists of American mathematicians who first published prior to 1992. See text for details.

Figure 3. Cohort effects in field choice**A. Fraction of dissertations in Soviet fields****B. Similarity index of dissertations**

Notes: The sample consists of all mathematicians who first published between 1978 and 2009, and use the subject classification of the first published paper to measure the likelihood that the dissertation was in a Soviet-style field and the dissertation's similarity index. The trends are smoothed using a 3-year moving average centered around the middle year in the interval.

Table 1. Summary statistics, sample of American mathematicians

Variable:	All mathematicians	Pre-1992 cohorts	Post-1992 cohorts
Number of mathematicians	78,684	34,318	44,366
Number of papers:			
Published 1940-2009	711,497	560,262	151,235
Published 1940-1991	330,370	330,370	---
Published 1992-2009	381,127	229,892	---
Percent of papers in Soviet fields:			
Published 1940-2009	.315	.326	.271
Published 1940-1991	.334	.334	---
Published 1992-2009	.298	.316	---
Similarity index:			
Published 1940-2009	.0269	.0273	.025
Published 1940-1991	.0272	.0272	---
Published 1992-2009	.0266	.0273	---
Dissertation paper:			
Percent of dissertations in Soviet fields	.281	.320	.251
Similarity index	.0245	.0263	.0233

Notes: The sample consists of all American mathematicians who first published between 1940 and 2009. The "dissertation" paper is defined to be the first paper published by a mathematician.

Table 2. Main fields of publications in the Soviet Union, 1984-1989

<u>Field:</u>	Share of papers published in the Soviet Union	Share of papers published in the United States
1. Partial differential equations	0.104	0.033
2. Ordinary differential equations	0.074	0.019
3. Quantum theory	0.068	0.059
4. Probability theory and stochastic processes	0.061	0.039
5. Global analysis, analysis on manifolds	0.048	0.039
6. Operations research, mathematical programming	0.044	0.071
7. Numerical analysis	0.043	0.043
8. Operator theory	0.031	0.019
9. Statistical mechanics, structure of matter	0.029	0.026
10. Functions of a complex variable	0.028	0.015

Notes: The paper counts in each field are obtained directly from the web-based AMS *Mathematical Reviews* database (*MathSciNet*) and consist of all papers published by mathematicians affiliated with Soviet or American institutions between 1984 and 1989.

Table 3. Effect of the Soviet supply shock on the rate of intellectual mobility

	Specification		
	(1)	(2)	(3)
A. Dependent variable = Paper in a field different from the dissertation			
Post-1992 indicator × Soviet-style dissertation	.123 (.006)	.123 (.006)	.129 (.005)
Post-1992 indicator × Tenured as of 1992	---	-.002 (.007)	-.007 (.006)
Post-1992 indicator × log(rate of output)	---	-.015 (.004)	-.006 (.004)
Post-1992 indicator × Soviet-style dissertation × Tenured as of 1992	---		.011 (.013)
Log(rate of output)	---		-0.024 (.010)
B. Dependent variable = Paper in a brand new field			
Post-1992 indicator × Soviet-style dissertation	.130 (.007)	.119 (.006)	.082 (.006)
Post-1992 indicator × Tenured as of 1992	---	-.001 (.004)	.003 (.004)
Post-1992 indicator × log(rate of output)	---	-.029 (.002)	-.019 (.002)
Post-1992 indicator × Soviet-style dissertation × Tenured as of 1992	---	---	-.046 (.012)
Log(rate of output)	---	---	-.087 (.009)

Notes: Standard errors are reported in parentheses and are clustered at the individual level. The sample consists of mathematicians whose first published paper was before 1992. All regressions include a vector of individual fixed effects, and a quartic control for years of experience. The “tenured as of 1992” variable indicates whether the mathematician had at least 10 years of experience as of 1992; the “log papers per year” variable gives the annual rate of publication of the mathematician between the year of entry and 1991. Both of these variables are demeaned. The regressions in Panel A have 525,944 observations, while the regressions in Panel B have 216,657 observations. The regression in Panel B exclude all spells after the mathematician first switches to a field different from the dissertation.

Table 4. Descriptive statistics for the duration of preparation spells

	Spell ends before 1992 with:		Spell ends after 1992 with:	
	American- style paper	Soviet-style paper	American- style paper	Soviet-style paper
A. Spell starts with:				
American-style paper	.963	1.221	1.156	1.295
Soviet-style paper	1.122	.756	1.294	.770
B. Mathematician wrote an American-style dissertation and spell starts with:				
American-style paper	.980	1.338	1.196	1.472
Soviet-style paper	.937	.595	1.189	.679
C. Mathematician wrote a Soviet-style dissertation and spell starts with:				
American-style paper	.816	1.015	.928	1.091
Soviet-style paper	1.335	.835	1.401	.810
D. Spell does not involve transition to a new field and the dissertation was:				
American-style	.977	.676	1.196	.812
Soviet-style	.796	.864	.911	.868
E. Spell involves transition to a new field and the dissertation was:				
American-style	---	2.195	---	3.418
Soviet-style	2.289	---	5.074	---

Notes: A preparation spell is defined as the length of time elapsed between a mathematician's consecutive papers (in years). The sample consists of American mathematicians whose first published paper was before 1992, and the data include all the preparation spells for each mathematician.

Table 5. Effect of the Soviet supply shock on the duration of preparation spells

Independent variable:	Specification		
	(1)	(2)	(3)
Soviet-style dissertation × post-1992 indicator ×:			
New field at end of spell	2.141 (.151)	1.847 (.169)	1.171 (.289)
Tenured as of 1992	---	.108 (.037)	.103 (.035)
Log papers per year	---	-.494 (.037)	-.475 (.036)
Soviet-style dissertation × post-1992 indicator × new field at end of spell ×:			
Tenured as of 1992	---	---	-.124 (.460)
Log papers per year	---	---	-.973 (.273)
American-style dissertation × post-1992 indicator ×:			
New field at end of spell	1.197 (.094)	1.042 (.037)	.745 (.224)
Tenured as of 1992	---	.056 (.030)	.060 (.030)
Log papers per year	---	-.542 (.028)	-.536 (.028)
American-style dissertation × post-1992 indicator × new field at end of spell ×:			
Tenured as of 1992	---	---	-.338 (.235)
Log papers per year	---	---	-.523 (.185)

Notes: Standard errors are reported in parentheses and are clustered at the individual level. The sample consists of mathematicians whose first published paper was before 1992. All regressions include the mathematician's experience (defined as a fourth-order polynomial), a vector of individual fixed effects, and a vector of year fixed effects. The regressions have 525,944 observations. The "new field at end of spell" variable is set to unity if the spell concluded with the mathematician publishing a paper in a field where he had never published before; the "tenured as of 1992" variable indicates whether the mathematician had at least 10 years of experience as of 1992; and the "log papers per year" variable gives the annual rate of publication of the mathematician between the year of entry and 1991. Both the tenure variable and the log papers per year variable are demeaned.

Table 6. Effect of the Soviet supply shock on the dissertation field of successive cohorts of American mathematicians

Variables:	Comparison group		
	Rest of world	Did not receive Soviet émigrés	Americans only
A. Soviet-style dissertation			
American mathematician	-.006 (.005)	-.024 (.007)	---
American mathematician × post-1992 indicator	-.055 (.006)	-.061 (.008)	---
Prolific mathematician	---	---	.054 (.013)
Prolific mathematician × post-1992 indicator	---	---	.033 (.017)
A. Similarity index of dissertation			
American mathematician	-.010 (.002)	-.022 (.003)	---
American mathematician × post-1992 indicator	-.027 (.004)	-.030 (.005)	---
Prolific mathematician	---	---	.040 (.010)
Prolific mathematician × post-1992 indicator	---	---	.023 (.001)

Notes: Standard errors reported in parentheses and are clustered by year of entry. The regressions use the sample of mathematicians whose first publication was between 1978 and 2009 (except in column 2, which use the 1984-2009 cohorts). The dependent variable in panel A is a dummy variable indicating if the mathematician's dissertation was in a Soviet field, while the dependent variable in panel B is the similarity index associated with the mathematician's dissertation. The dummy variable indicating if the mathematician is "prolific" is set to unity if the mathematician published more than one paper in the year he entered the mathematics community. The regressions have 391,408 in column 1; 166,636 observations in column 2; and 66,818 observations in column 3. All regressions include a vector of year-of-entry fixed effects.

APPENDIX TABLE A-1. Age-specialization profiles

Independent Variable:	Dependent variable			
	Percent of papers published at time t that are Soviet-style	Similarity index at time t	Percent of papers up to time t that are Soviet-style	Log number of fields up to time t
$A_i \times$:				
T_i	0.021 (.006)	-.014 (.003)	-.011 (.001)	.005 (.004)
Experience	.118 (.016)	.046 (.008)	.139 (.004)	.955 (.013)
Experience ²	-.080 (.016)	-.033 (.008)	-.086 (.004)	-.372 (.013)
Experience ³	.024 (.006)	.011 (.003)	.023 (.002)	.083 (.005)
Experience ⁴	-.0026 (.001)	-.001 (.001)	-.002 (.0002)	-.007 (.001)
$A_i \times T_i \times$:				
Experience	-.029 (.030)	-.003 (.015)	-.058 (.008)	-.103 (.024)
Experience ²	.034 (.025)	.008 (.013)	.049 (.007)	.102 (.021)
Experience ³	-.014 (.008)	-.004 (.004)	-.016 (.002)	-.033 (.007)
Experience ⁴	.002 (.001)	.001 (.001)	.002 (.0002)	.003 (.001)
$A_i \times$:				
T_i	---	---	---	---
Experience	-.206 (.023)	-.073 (.012)	-.266 (.006)	1.2003 (.019)
Experience ²	.071 (.026)	.010 (.013)	.153 (.007)	-.574 (.021)
Experience ³	-.013 (.010)	.004 (.005)	-.043 (.003)	.152 (.008)
Experience ⁴	.001 (.001)	-.001 (.001)	.004 (.0003)	-.015 (.001)
$A_i \times T_i \times$:				
Experience	-.146 (.042)	-.114 (.021)	-.014 (.011)	-.033 (.034)
Experience ²	.074 (.038)	.075 (.019)	-.025 (.010)	.112 (.030)
Experience ³	-.018 (.013)	-.022 (.007)	.015 (.003)	-.053 (.011)
Experience ⁴	.002 (.002)	.002 (.001)	-.002 (.001)	.007 (.001)

Notes: Standard errors are reported in parentheses. "Years of experience" is defined as the number of years elapsed at time t since the first publication, is divided by 10, and is demeaned. The variable S_i is set to unity if the mathematician's dissertation was in a Soviet field; $A_i = 1 - S_i$; and T_i is a dummy variable indicating if the observation represents a year after 1992. All regressions have 199,251 observations and include a vector of individual fixed effects and a vector of calendar year fixed effects.